

# A COMPARISON OF THE STYLES OF DEFORMATION ASSOCIATED WITH TWO RECENT PUSH MORAINES, SOUTH VAN KEULENFJORDEN, SVALBARD

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## ABSTRACT

In this paper, two push moraine systems associated with two small subpolar glaciers, Finsterwalderbreen and Penckbreen, were investigated. This study showed that at these glaciers the push moraines were formed in association with surges, which produced a different style of moraine depending on the rheology of the deformed material and the glacial history. The moraines are similar in that they are formed by folded outwash sediments and contain little till. However, the forms of these moraines are very different. The Penckbreen moraine is composed of a lower shallow marine sand, silt and clay, and an upper fluvial sand and gravel. Deformation at this site led to the formation of large anticlines in the silts and clays, with disharmonic smaller folds and thrusts in the upper gravels, above a detachment surface between the fine-grained and overlying coarse-grained lithologies. This deformation decreases towards the foreland, with marine and fluvial sediments responding differently because of their different rheological properties. This moraine was formed during one surge event which occurred during the early 19th century. In contrast, the Finsterwalderbreen moraine is composed of outwash sand and gravel, and was formed as the result of a series of surge events. These advances all reached a similar limit and occurred at regular intervals. © 1997 John Wiley & Sons, Ltd.

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## INTRODUCTION

This is a study of the push moraine systems associated with two small subpolar valley glaciers, Penckbreen and Finsterwalderbreen, which are situated on the southern side of Van Keulenfjorden, southern Svalbard (Figure 1). The moraine systems are thought to have been formed during glacial surges, which have produced a dramatic landscape dominated by these large push moraines (Figure 2) (Liestøl, 1969; Croot, 1988a).

Studies of glaciotectionic deformation are increasing at present (e.g. three recent collections of papers on the subject: van der Meer, 1987; Croot, 1988b; Aber, 1993) because of increased awareness that glaciotectionic deformation is an important component of glacier dynamics (Boulton and Jones, 1979; Clarke, 1987; Hart and Boulton, 1991). Push moraines form due to proglacial deformation, which can result from either the marginal bulldozing of pre-existing sediment, or from a combination of both frontal pushing and the movement of subglacial deforming material out into the glacial foreland (Hart, 1990).

Push moraine formation is common both today and during the Pleistocene, and combined with their relative accessibility (compared to subglacial deformation) they have been the focus of numerous studies (see Aber, 1996). This includes a number of detailed studies from modern arctic glaciers (e.g. Holmströmbreen, Svalbard (Gripp, 1929; Boulton *et al.*, 1989), Uversbreen, Svalbard (Hambrey and Huddart, 1995), Erikbreen and Usherbreen, Svalbard (Etzel Müller *et al.*, 1996), Pedersenbreen, Svalbard (Bennett *et al.*, 1996), Maktak glacier, Baffin Island (Boulton, 1986), Thompson glacier, Axel Heiberg (Kälin, 1971; Lehmann, 1992) and Eyjabakkajökull, Iceland (Croot, 1988c), as well as studies of Pleistocene push moraines (e.g. Bride Moraine,

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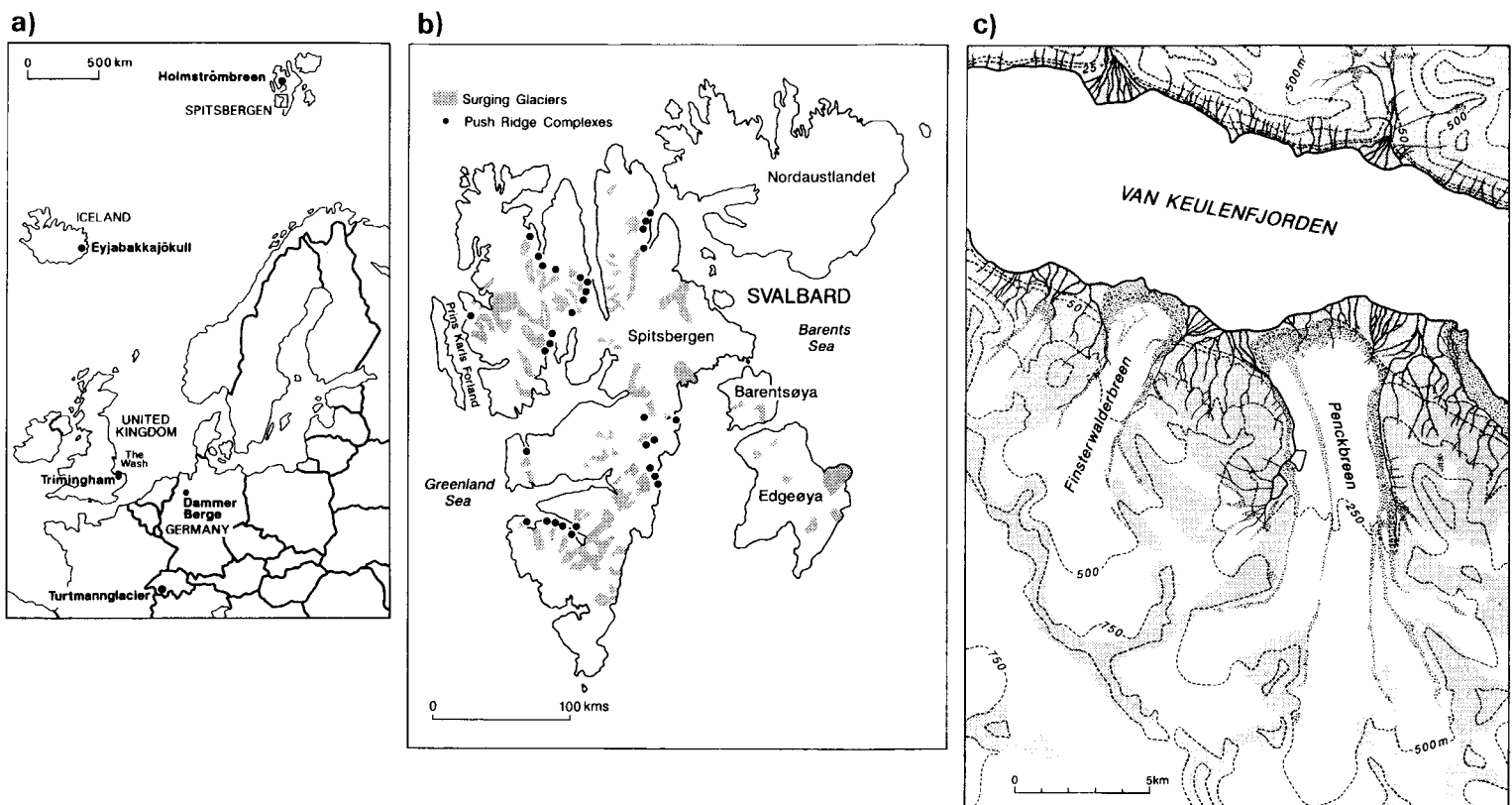


Figure 1. Site location maps: (a) location of the sites mentioned in the text; (b) location of surging glaciers and push ridge complexes in Svalbard (after Croot, 1988a); (c) location of Penckbreen and Finsterwalderbreen (also located by the outlined box (a))



Figure 2. Photographs of: (a) Penckbreen push moraine; (b) Finsterwalderbreen push moraine

Isle of Man (Thomas, 1984), Cromer Ridge, UK (Hart, 1990), Dammer Berge, Germany (van der Wateren, 1987), Melabakkar-Ásbakkar, Iceland (Ingólfsson, 1988; Hart, 1994) and Lake Pukaki, New Zealand (Hart, 1996a). In this paper, we show the results from the detailed investigations of the two sites and go on to compare these with other push moraines formed by surging and non-surging glaciers.

### USING LICHENOMETRY TO DATE PUSH MORaine FORMATION

In arctic areas, lichens are often the only way to date landscape-forming events, because of the lack of historical records. Lichens can be used to find both relative and absolute dates. However, lichenometry can be problematic since lichen growth is not simply related to age (for discussion of the problems and techniques, see Locke *et al* (1979)). The dating of push moraines is even more difficult because lichens may have been already growing on the land surface prior to the deformation event. At the two push moraine sites discussed below, it will be shown that the push moraines formed from the proglacial compression of pre-existing outwash surfaces.

Werner (1990) produced a growth curve for *Rhizocarpon* based on known historical dated surfaces in Svalbard, based on measuring the short-axis average of the five largest thalli to date the lichens. His results are shown in Figure 3, and a polynomial trendline fitted through these data gives a lichen as follows:

$$y = 0.38x^2 + 0.81x + 41.1 \text{ (where } R^2 = 0.89 \text{)}$$

Given this curve, the push moraine surfaces were dated in the following way (see Figure 4).

1. During time **a** the outwash fan forms and the lichens growth to size **x**.
2. At time **b** the glacier surges to form a push moraine.
3. At time **c** the ice sheet retreats and a new outwash surface is produced, and the lichens grow on both surfaces.
4. This process is repeated during times **d** and **e**, etc.

The last surge ( $S_n$ ) (time **d**) must reflect the current date (taken as 1995) minus the time to produce the largest lichen formed in zone 3 ( $Y_n$ ), and the first surge ( $S_{n-1}$ ) (time **b**) must reflect the current date minus the time to produce the largest lichen formed in zone 2 ( $Y_{n-1}$ ). That is:

$$S_n = 1995 - Y_{n-1}$$

This method was used to date the surge events and will be discussed in more detail below.

### PENCKBREEN

This is the larger of the two glaciers and presently is melting into a lake held up between the moraines and the glacier front (Figure 5). The foreland consists of two areas of differing sedimentology, structural geology and land surface consolidation: (a) an outer consolidated gravel surface with some lichen cover (zone A); and (b) an

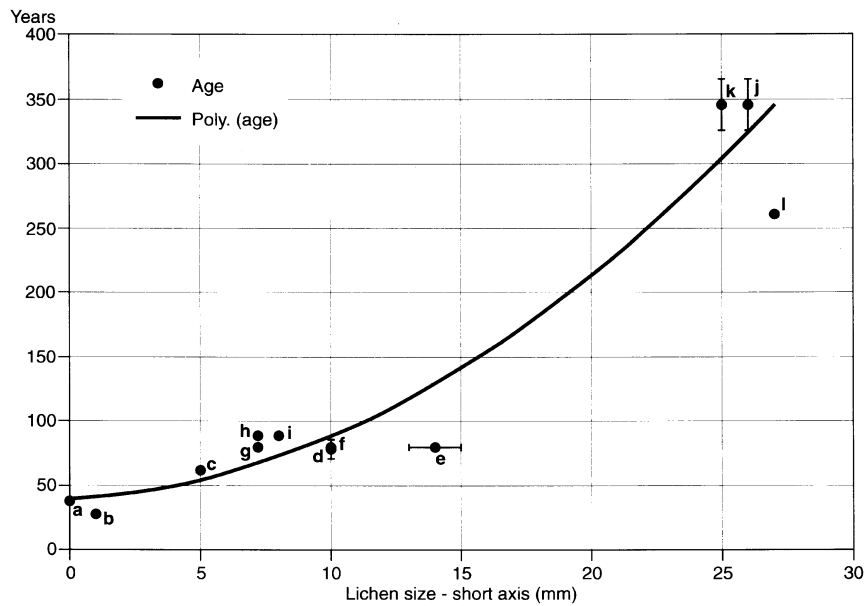


Figure 3. Lichenometry curve after Werner (1990)

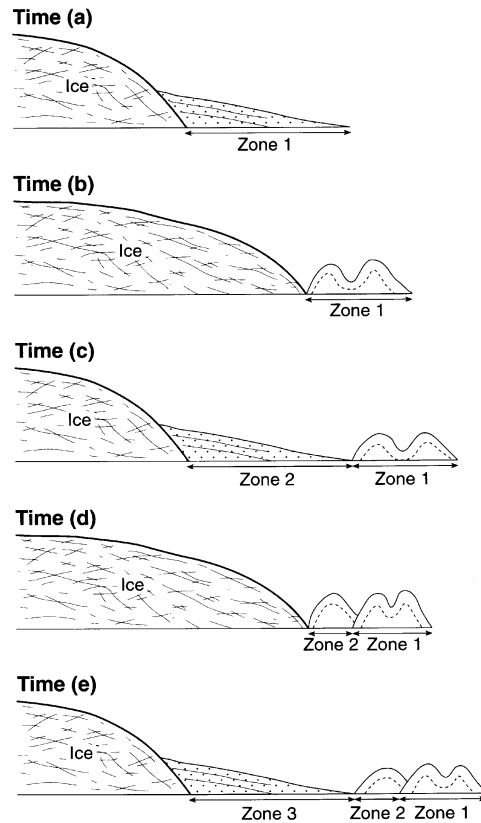


Figure 4. Schematic diagram to show how to calculate age of deformation events from lichen data (see text for details)

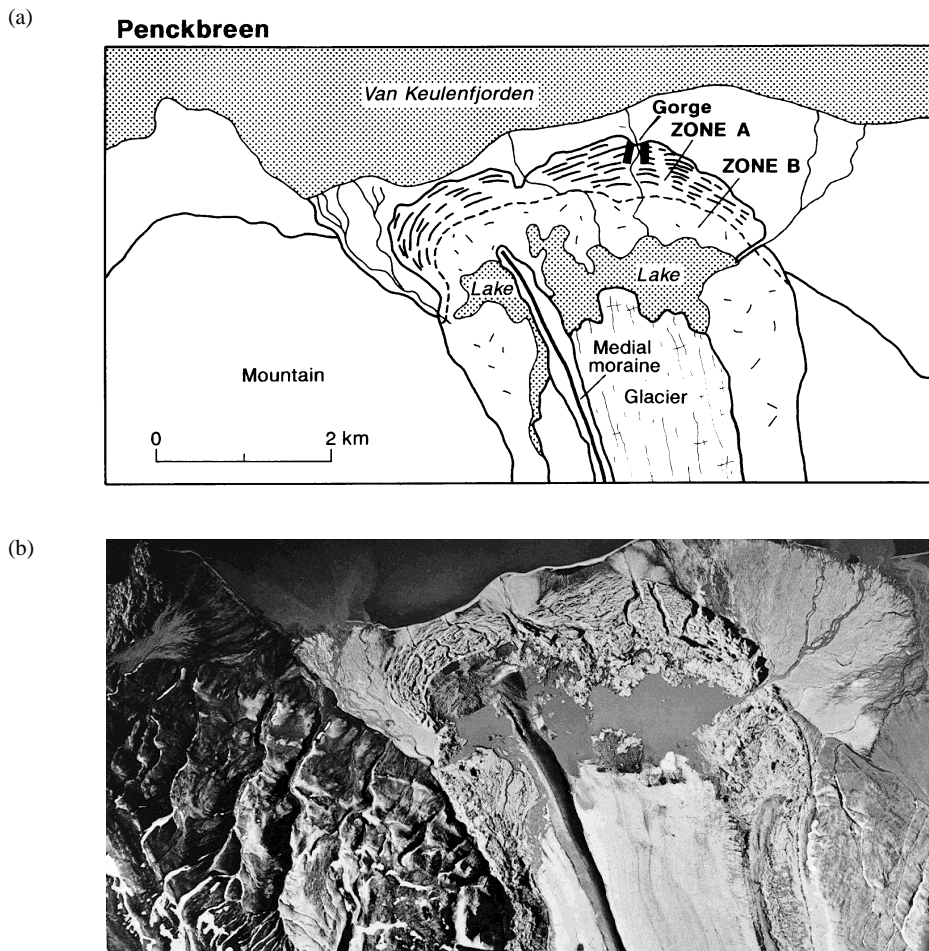


Figure 5. Penckbreen: (a) geomorphological map, showing location of the western gorge; (b) air photograph

inner unconsolidated and unvegetated surface composed of poorly sorted diamicton, gravel and finer-grained laminated sediments (zone B).

The major moraine system at Penckbreen (zone A) consists of a series of ridges which appear to relate to one push event. The moraine is composed of two distinct facies: (a) a lower unit (over 20 m thick) of laminated sand, silt and clay; and (b) an upper unit of gravel (maximum thickness 5 m). The lower sand, silt and clay unit contains many shells and is interpreted to represent shallow marine sediments from the old fjord bed. The upper gravel unit represents outwash sediments deposited in a high-energy fluvial environment.

The surface of the moraine is composed of this outwash sediment, with well developed bars. However, the bars bear no relationship to the modern-day landscape. Thus, we suggest that this represents a low-angled fan surface (similar to those being formed today (Figure 6a)), that has been subsequently deformed. The bars that constitute the fan surface are very useful in identifying the style of deformation (Figure 6a and 6b): if the bars can be traced from one moraine ridge to another (Figure 6c) then the surface has been folded; but if they cannot be traced then faulting must have occurred (Figure 6c and 6d).

In contrast, zone B is composed of very irregular hummocky topography with many active sediment gravity flows. In places, there is evidence of small-scale deformation, and the formation of small (1 m) push moraines. We suggest that this zone was formed in association with glacier retreat after the formation of zone A. The landscape was formed by a combination of proglacial processes: (i) small-scale proglacial deformation; (ii) normal lacustrine and fluvial sedimentation; and (iii) dead-ice melting. These processes result in the formation

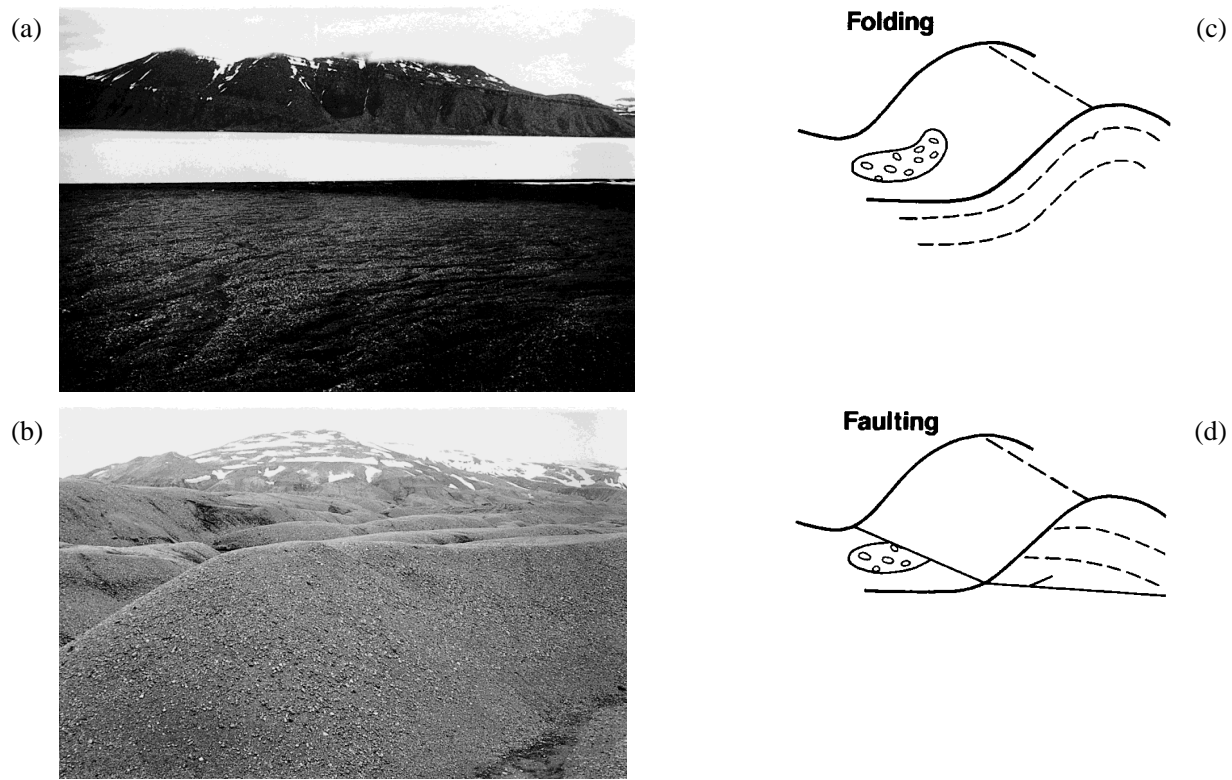


Figure 6. Deformation in zone A at Penckbreen. (a) Photograph of a modern-day alluvial fan at Penckbreen; this is an analogue for the proglacial landscape at Penckbreen prior to the proglacial deformation. (b) Photograph showing the ridges that compose the Penckbreen push moraine. Theoretical deformation patterns of the fluvial bars that form the upper gravel at Penckbreen: (c) folding; (d) faulting

Table I. Lichenometry data

Glacier	Zone	Lichen short axis (mm)		Y (years)	Age of surge (AD1995– $S_{n-1}$ )	Interval between surges (years)
Penckbreen	A	17		166	less than 1829	–
Finsterwalderbreen	1a	49		993	1564	–
	1b	29				
	1c	30	31	431	1696	132
	1d	33				
	1e	25		299	1800?	104?
	2	0		0	1904*	104?

\* Known age

of hummocky moraine (Sugden, 1970; Boulton, 1971; Benn, 1992). Thus, it is very likely that the boundary between zones A and B marks the ice margin of the glacier that formed the large push morainic system (zone A).

#### *Age of the moraine*

The age of last glacier surge is not known but is suggested by Croot (1988a) to have occurred during the 1800s. The study of lichens on the moraine ridges indicated that there was no significant change in the size of lichens across the form of the moraine. Instead it could be argued that the moraine was on one age. The push moraine lichen-dating method discussed above cannot be used for this moraine because only the maximum age of the outwash surface can be calculated (Table I). However, using the lichen curve of Werner (1990) it can be shown that the push moraine was formed sometime since AD 1829.

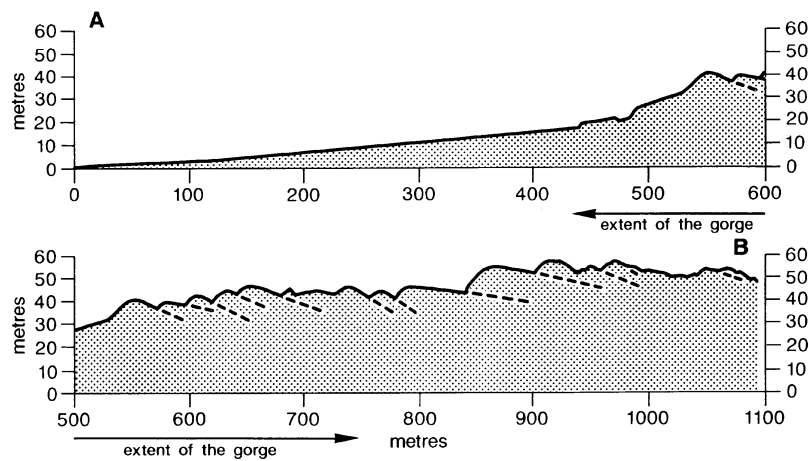


Figure 7. Transect of the Penckbreen push moraine: the dashed lines show the thrust ridges, whilst the unmarked ridges were folded

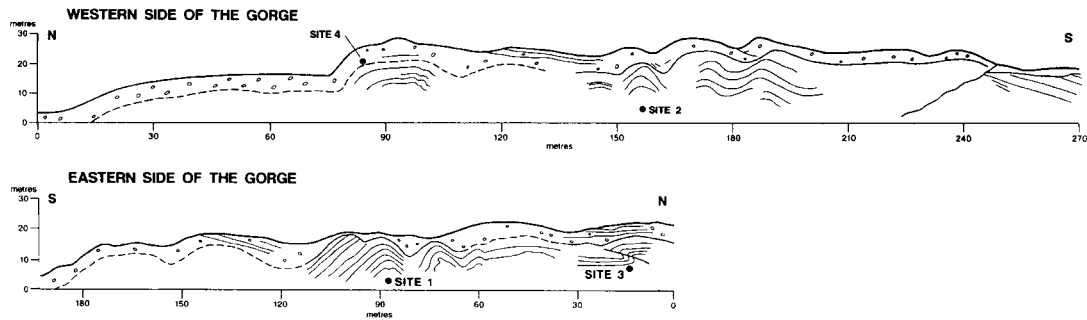


Figure 8. Detail of the gorge section at Penckbreen

### *Structures within the push moraine*

The shape of the moraines was recorded accurately along a transect (Figure 7) which was taken perpendicular to the strike of the push moraine. The nature of each ridge was recorded according to the 'bar tracing' method, i.e. whether it was due to folding or faulting. The most distal part of the section (0–450 m) was composed of the modern-day alluvial fan and on the proximal side of this there is a small moraine composed entirely of gravel (450–480 m). The main part of the push moraine is from 480 to 1100 m and it shows that the height of the moraine gradually increases towards the proximal zone. In this zone there are 20 ridges, of which 60 per cent were produced by faulting. The faulted ridges also tends to have an asymmetrical profile, with a steep distal slope and a shallow proximal slope, whilst the folded ridges are more symmetrical in shape. A gorge in the western part of the moraine provided the opportunity to observe the styles of deformation within the Penckbreen push moraine (location shown in Figure 5). Figure 8 shows the complete section, in which four sites were investigated in detail. The first three sites are in the lower sand, silts and clays whilst the last sites was at the junction with the gravel.

*Site 1.* This is a 5 m by 3 m section of rhythmic sand and clay with shells which has been deformed into an anticline (Figure 9a). The strike of the feature is  $72^\circ$  with limb dips of  $50^\circ$  and  $44^\circ$  respectively. Towards the centre of the anticline the bedding is broken up into detached sand boudin-like features. Dahlstrom (1970) suggested that this style of deformation resulted from early extensional strain within a basal shear zone (associated with décollement), which was subsequently reformed by horizontal compression (which produces a stacking of the boudins in the centre of the open folds).

At the top of the fold there is chevron folding (Figure 9b): this style of folding is commonly found in layered graded sequences such as turbidites, estuarine sediments and varves (Ramsay, 1974) and has previously been

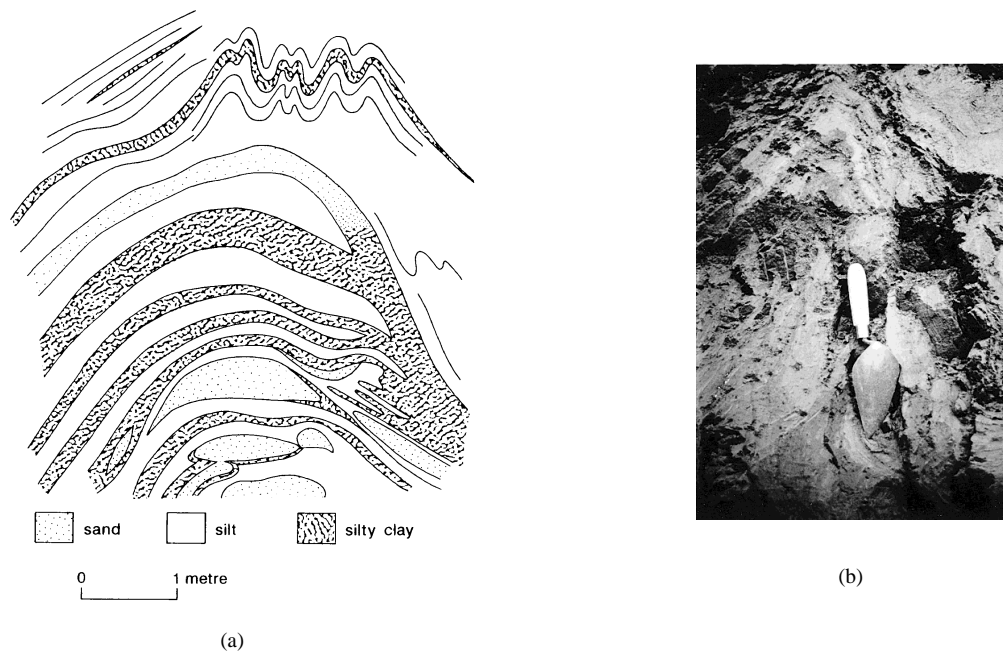


Figure 9. Penckbreen site 1: (a) sedimentology; (b) photograph of the chevron folding

reported associated with the proglacial deformation of varves (Hart, 1990). The best conditions for chevron folding include the presence of a high-competence contrast between the bedding, and a principal axis of compression parallel to layering (Ghosh, 1968; Paterson and Weiss, 1966). The strike of the chevron folds is  $97^\circ$ , and the limb dips are  $30^\circ$  and  $55^\circ$ .

Thus, at this site, there may have been initial detachment of the sediment from the base, and the block may have moved as a nappe in front of the glacier. At the base of the nappe, extensional deformation (simple shear) occurred. Once the block stopped moving, horizontal compression occurred (pure shear) leading to the formation of the open folding.

In order to compare the deformation at various sites, the minimum longitudinal strain associated with proglacial deformation can be calculated by the following equation:

$$e = \frac{\text{Deformed length} - \text{Original length}}{\text{Original length}} \times 100$$

Table II. Calculation of strain at Penckbreen

Site	Location	Strain (%)
1	chevron folds	-31
	chevron folds	-32
	sand layer	-25
	sand layer	-21
	sand layer	-41
2	sand layer	-32
	silt layer	-34
3	sand layer	-59
4	silt layer	-66



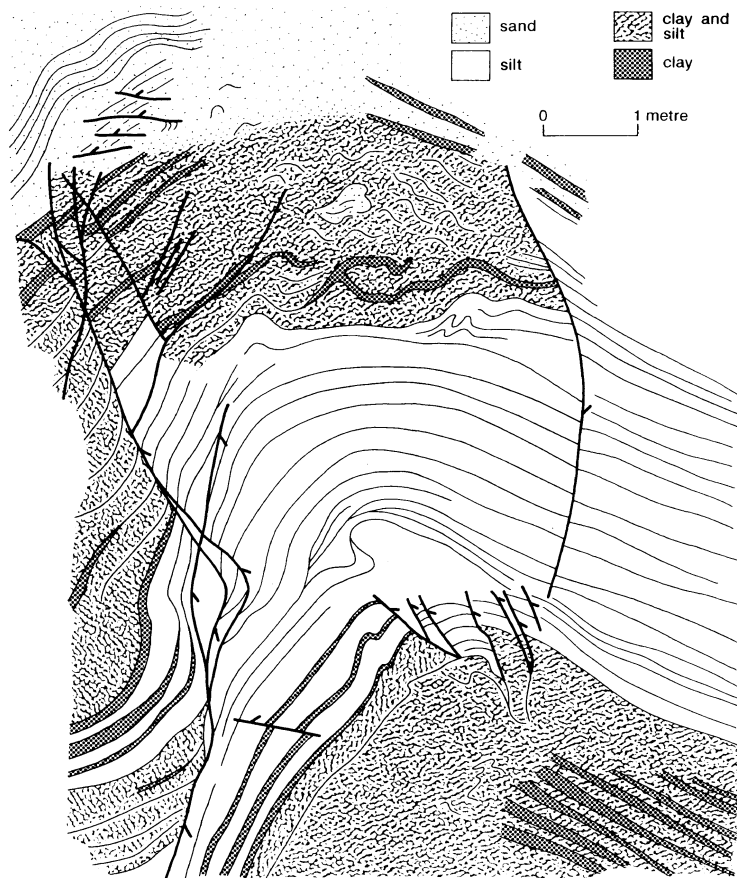


Figure 10. Sedimentology at Penckbreen site 2

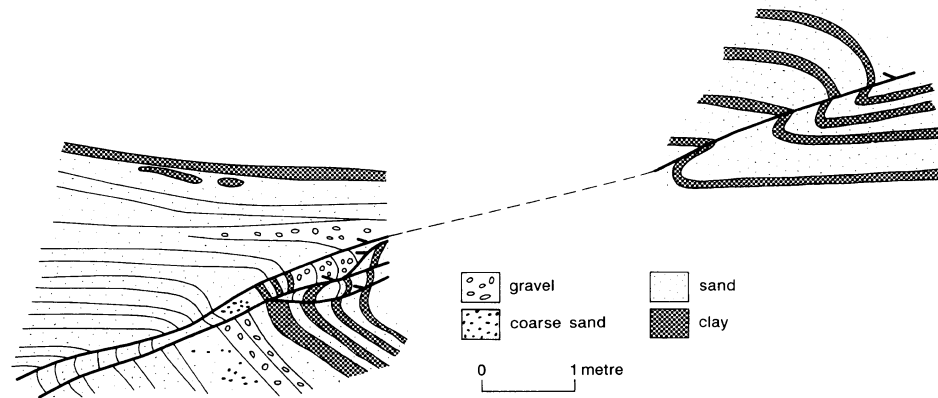
The results are shown in Table II, and indicate a minimum average shortening of  $\sim 30$  per cent for site 1.

*Site 2.* This feature also consists of an anticline, but the cleared section is much larger, 8 m by 9 m (Figure 10). The section is composed of sand, silt and clay with marine shells, but at this site there is more clay than at site 1. The core of the anticline is cut by a number of faults. On the proximal limb there is a normal fault with a strike of  $145^\circ$ ,  $64^\circ$  dip and a throw of 0.1 m. On the distal limb there are more complex conjugate reverse faults, which have an average strike of  $166^\circ$ , dip  $66^\circ$ . Towards the top of the fold there are some low-lying reverse faults, with a strike of  $135^\circ$ , dip  $22^\circ$ . In the centre of the fold there are some small splaying reverse faults, and a recumbent fold. At the top of the anticline there are some sand boudins. Overall, the laminated beds have behaved in a brittle manner, whilst the more massive clay and silt beds have deformed in a more ductile manner.

Although this structure shows overall evidence for compressive deformation, it also contains extensional elements. The boudinage of the sand within the anticline could reflect either initial extensional deformation within the basal zone of the nappe (as at site 1) or layer extension associated with the anticline formation. As the anticline developed, this produced conjugate faulting on the distal limb, recumbent folding and reverse faulting at the anticline hinge, décollement within the core and low-angled reverse faulting. This may also have been associated with extension on the proximal limb, resulting in the normal faulting. The average strain at this site was *c.* 33 per cent, which was very similar to site 1.

*Site 3.* This site contains a large reverse fault in rhythmically bedded sand, silt and clay (Figure 11). The fault has a series of parallel faults beneath it and a maximum throw of 2 m. The average strike of this fault is  $103^\circ$  with a dip of  $30^\circ$ . This fault extends for 8 m after which it dies out. The section becomes more gravel-rich in the

(a)



(b)



Figure 11. Penckbreen site 3: (a) sedimentology; (b) photograph of the large-scale reverse faulting

distal direction and we suggest that the distal gravels have taken up the deformation. This feature is also typical of compressive deformation and the strain at this site was calculated to be  $-59$  per cent.

*Site 4.* This site shows the contact at the distal edge of one of the moraines (Figure 12). This section is 3 m by 2 m and shows that the top of the shallow marine material and the base of the gravel are both folded and sheared. The base of the section could not be further excavated due to the presence of permafrost. The site shows two fold noses of shallow marine material and a series of reverse faults both within the gravel and also at the boundary. It is clear that the gravel behaved more competently and was deformed in a brittle manner whilst the shallow marine material behaved in a more ductile manner. Figure 13 shows a schematic diagram to illustrate the development of this structure. Originally the gravel overlaid the shallow marine material (Figure 13a) but as compressive deformation occurred, the boundary was first deformed into two open folds (Figure 13b) that were then overturned and faulted (Figure 13c). An estimation of minimum strain at this site was calculated to be  $-66$  per cent.

### Interpretation

The results from the five sites and the overall section indicate that there is a great deal of evidence for compression, i.e. folding (open and chevron) and reverse faulting (large and small scale), but that the sediments behaved in a different way depending on their rheology. This could be seen on a small scale with clay-rich sediments producing ductile deformation, clay and sand rhythmites producing chevron folds, and sand-rich rhythmites producing more brittle deformation. However, this can also be seen on a larger scale where the gravel and marine sediments behaved very differently, with the marine sediments forming large open folds whilst the gravels detached along their base and produced smaller-amplitude and larger-wavelength folds and faults (Figure 14a).

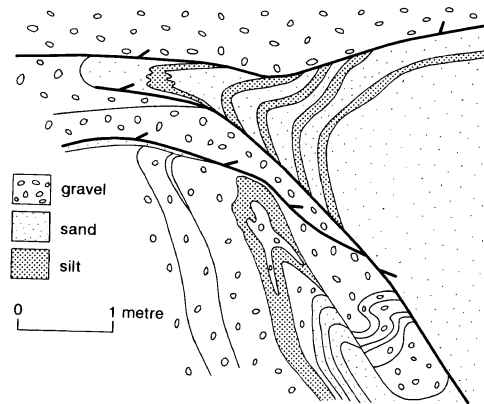


Figure 12. Sedimentology at Penckbreen site 4

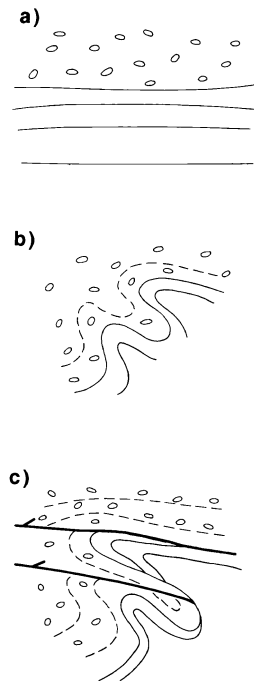


Figure 13. Schematic diagram to show the development of the deformation at site 4

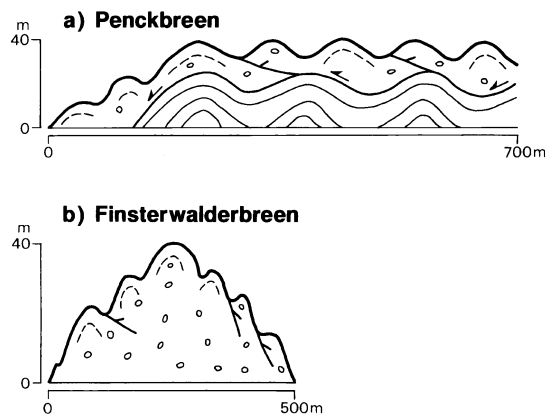


Figure 14. Schematic diagrams to show the internal structure and external shape of the two push moraines

Similarly, calculations of strain varied throughout the section depending on the local rheology. However, in order to calculate the strain over the whole section we need first to calculate the maximum longitudinal strain in the gorge section. Using a sand layer in the shallow marine sediments as a strain marker, the result of total shortening is  $-31$  per cent. This can be compared with using the land surface as a strain marker over a similar section, which gives a shortening of only  $-18$  per cent, i.e. 58 per cent of the maximum value. If we use the land surface as a strain marker over the whole moraine, and apply this scaling factor, we should have an estimation of longitudinal strain over the whole section. This is calculated from Figure 7 to be  $-26$  per cent.

#### FINSTERWALDERBREEN

This is the smaller of the two glaciers, and surging last occurred between 1898 and 1910 (Liestøl, 1969; Nuttall *et al.*, 1996). A geomorphic map of the glacier and its foreland is shown in Figure 15. The glacier foreland consists of two zones in a similar way to Penckbreen: (a) an outer zone of push ridges, and (b) an inner zone of chaotic topography.

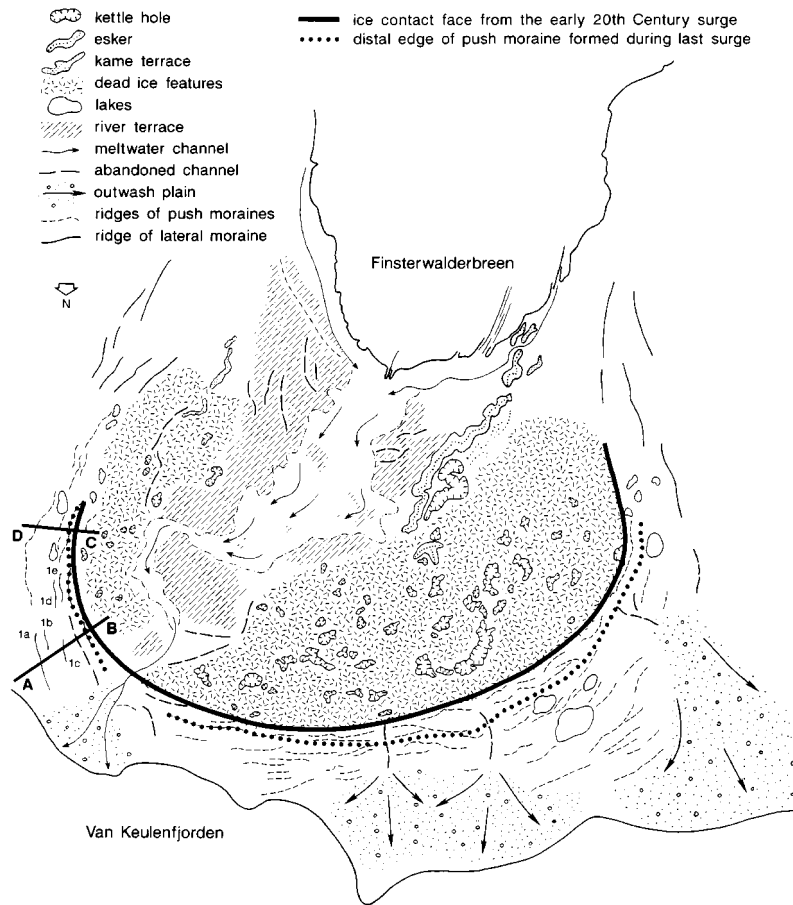
Unlike Penckbreen, however, the push ridges in the outer zone of Finsterwalderbreen show different levels of land surface consolidation, vegetation cover and lichen growth (zones 1 and 2). Gorges cut through the push moraine reveal that the moraine is composed mostly of coarse gravels with some thin silt beds, and observations of clast patterns on the surface of the moraine reveal the presence of the palaeobars (often unrelated to the modern landscape). Thus, we suggest that the push ridges of the outer zone represent a braided fluvial outwash system that was subsequently deformed by proglacial deformation. Lichenometry was also carried out using the same technique as discussed above in order to attempt to date the age of the proglacial deformation.

The outer zone of the push moraine can be broadly divided into two zones (shown in Figure 15) based on similar land surface consolidation and lichen growth. Zone 1 has a well consolidated land surface and is composed of a series of ridges with different sized lichens. Zone 2 shows no lichen growth, and has a very unconsolidated land surface; we suggest this latter zone was formed during the early 20th century surge.

Two detailed studies were made on the eastern side of the moraine, which are shown in Figure 16. Section AB has a high distal moraine, with more proximal ridges becoming progressively smaller. Section CD has the highest ridge in a more proximal position and contains only three distinct subzones. Section AB may have suffered distal marine erosion, and probably the true shape of the moraine is similar to that shown schematically in Figure 16. Since the moraine was composed mostly of gravel, large-scale structures were not present as at Penckbreen. However, from the surface, using the 'bar tracing' methods it was clear that both folding and faulting had occurred.

A detailed study was made of the lichens on these ridges (results shown in Table I) and Figure 17. These show that in zone 1, the inner and outer moraines (1a and 1e respectively) had discrete average lichen sizes, but that the three intermediate moraines (1b, 1c and 1d) had very similar average lichen sizes. Thus, we have grouped these

(a)



(b)

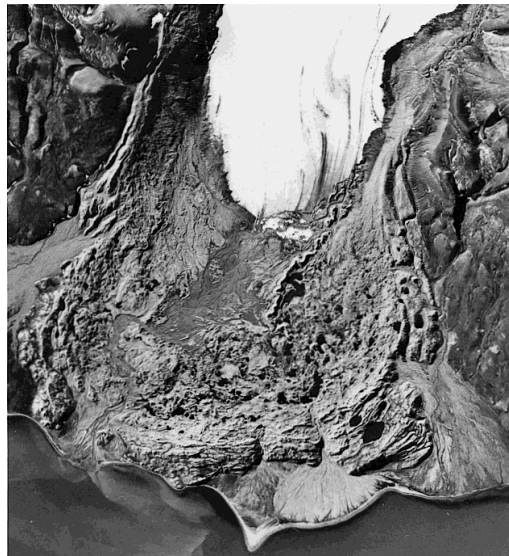


Figure 15. Finsterwalderbreen: (a) geomorphic maps; (b) air photograph

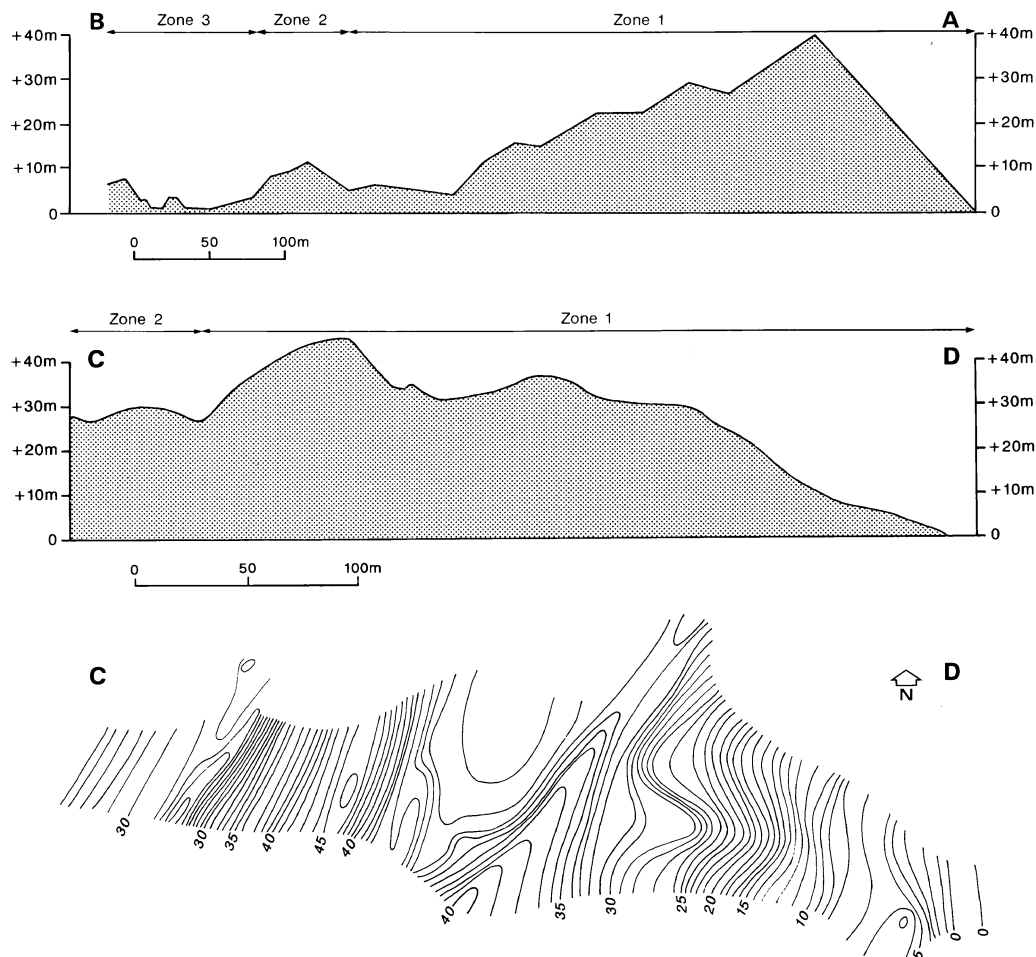


Figure 16. Two sections across the moraines at Finsterwalderbreen: section AB and section CD (see Figure 15 for location of these transects)

three together and suggest that they were formed at the same time. Once these intermediate moraines are taken as one, the average lichen sizes decrease along a distal to proximal transect of zone 1.

In order to calculate the age of the push moraine-forming events, the lichenometry technique discussed above was used. The date of the last surge was taken to be 1904 (a date midway between the pre- and post-surge observations). The results indicate that the first moraine-forming event (1a) occurred in AD 1564 and the second (1b, 1c and 1d) occurred in AD 1696. The age of ridge 1e is also impossible to calculate using the method discussed above; however, an intermediate between the known and previously calculated date would be AD 1800. This gives an average time interval between the moraine-forming events of 113 years.

However, there are a number of problems with this method; in particular, each push event will deform the earlier push events, and maybe also cause erosion. Also lichenometry may not have sufficient resolution to record individual readvances, since the measurement errors are potentially very great. In addition to this, there is the problem of the pre-existing outwash surfaces and the possibility of anomalous inputs of older material, maybe from supraglacial sources.

The inner zone of the push moraine at Finsterwalderbreen (zone 3) consists of a complex topography composed of:

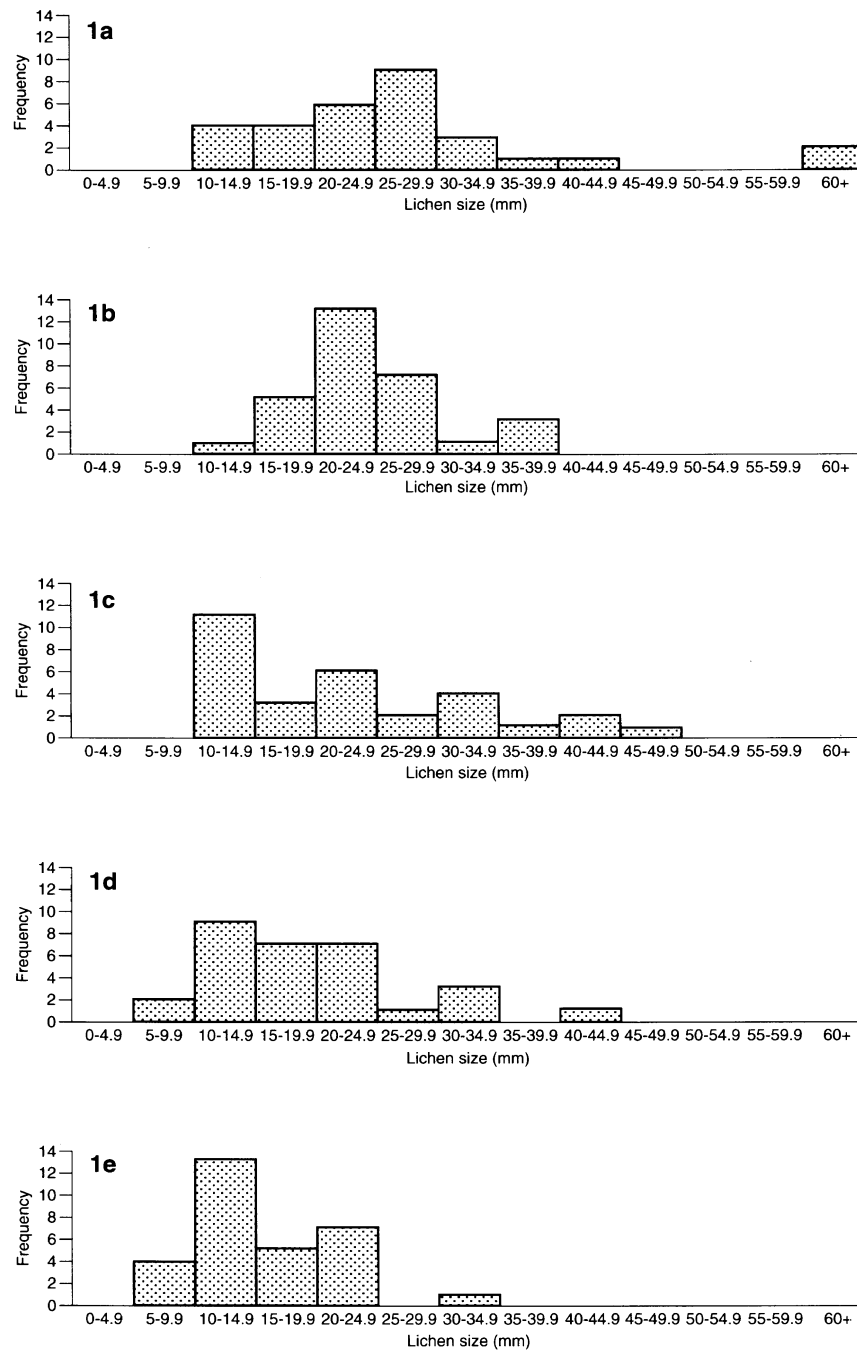


Figure 17. Lichen results from Finsterwalderbreen

- (i) a series of fluvial surfaces, some of which contain buried ice: where there is either no buried ice or the buried ice is still frozen, intact terraces and kame terraces (formed at the side of the glacier) have formed; where buried ice has melted, pitted outwash terraces and hummocky moraine/kames have formed;
- (ii) small single push moraines formed as the glacier retreated since 1904;

(iii) a large esker which was exposed after 1970.

Because the deformed outwash gravel at Finsterwalderbreen contains no continuous record of the bedding, strain could only be estimated from the moraine land surface. Using the scaling technique found from Penckbreen, the strain over section CD is –20 per cent and over section AB –44 per cent, so the average strain was calculated to be –32 per cent.

## DISCUSSION

Penckbreen and Finsterwalderbreen are adjacent glaciers with similarly extensive push moraines; however, they show important differences. The Penckbreen moraine was formed during one push event which deformed shallow marine and outwash sediments into a series of upright and overturned open folds. In general, the deformation decreased down-ice (except in local areas, e.g. site 4), with marine and fluvial sediments responding differently to the gravel because of their different rheological properties. This produced a push moraine 650 m long. We suggest that this large moraine was formed because the shallow marine sediments were relatively weak and because of the presence of a basal décollement surface in the shallow marine sediments.

This moraine is very similar to that observed at Holmströmbreen by Boulton *et al.* (1989), which was formed by one large push event and had a basal unit of shallow marine muds, silts and sands. The push moraine at Holmströmbreen was formed during a surge in 1890, and it is very likely that Penckbreen was formed during a similar surge in the early 19th century. Since there is no record of any previous surging recorded in these sediments (or those at Holmströmbreen), the nature or ages of previous surges is not known.

In contrast, the Finsterwalderbreen moraine was formed as the result of a series of advances. From historical records it is known that the glacier surged in the early 20th century, but the nature of the early readvances is not known. It is known that push moraines form in front of both surging and non-surging glaciers (Eybergen, 1987; van der Wateren, 1987; Hart, 1990; Etzelmüller *et al.*, 1996; Hambrey *et al.*, 1996), and it has also been argued that surging glaciers do not produce unique landscapes (Hart, 1996b). However, it can be seen that each readvance event reached a similar location, which may reflect a surge rather than a climatically driven readvance (which may have reached different locations in the foreland reflecting different climatic changes). If we assume that these readvances do reflect surges then from the lichenometry data we can suggest that these occurred on an average time interval of 113 years. It is very likely that this is an overestimation because of the problems with the lichenometry technique. However, Penckbreen has a similarly long quiescent period since it has not surged since the early 19th century (maximum time since surge, 166 years).

The results are similar to those of Dowdeswell *et al.* (1991) who suggested that Svalbard glaciers have a longer surge duration than glaciers in other parts of the world, with lower velocities and a longer quiescent period. Liestøl (in press) reported 50 years for Turnabreen, 70 years for Hambergbreen and 110 years for Recherchbreen. However, Svalbard was the only high-arctic region investigated so they could not determine if this longer duration was due simply to low temperatures or to other factors.

At Finsterwalderbreen, the surge events were more localized and only affected outwash sediments. We suggest that each surge moraine was much shorter at Finsterwalderbreen because: (a) the outwash sediments are far more competent than the shallow marine sediments; (b) there was no laterally extensive fine-grained basal décollement surface; and (c) there was a large obstacle to deformation in the form of the previous push moraine.

A similar push moraine composed of asynchronous elements has been found at Usherbreen, Svalbard, and is described by Etzelmüller *et al.* (1996). This moraine was finer-grained than Finsterwalderbreen, being composed of sand-rich pebbles, pebbles, sandy loam, sand, silt, clay and ground/glacier ice. However, the most recent deformational event at this site caused deformation throughout the whole moraine belt, but caused new push moraines to be formed at the distal end of the moraine belt. Additionally, the overall form of the push moraine at Finsterwalderbreen is very similar (although much larger) to the gravel-rich Turtmann glacier push moraine in Switzerland (Eybergen, 1987) (although that was formed in association with one push event).



The strains in the two sections were similar, –26 per cent at Penckbreen and –32 per cent at Finsterwalderbreen. These figures compare favourably with earlier estimates of strain from other sites associated with proglacial glaciotectionic deformation (see Table III).

Table III. Characteristics of various push moraines

Example	Strain (%)
Penckbreen, Svalbard	–26
Finsterwalderbreen, Svalbard	–32
Holmströmbreen, Svalbard (Boulton <i>et al.</i> , 1989)	–43
Eyjabakkajökull, Iceland (Croot 1988c)	–46
Melabakkar-Asbakkar, West Iceland (Hart, 1994)	–32
Trimingham, East Anglia, UK (Hart 1990)	–32

## CONCLUSION

This study showed that the push moraines at the two glaciers were formed in association with surges which produced a different style of moraine depending on the rheology and glacial history. The Penckbreen moraine was formed by one advance into a two-layer proglacial sequence. This sequence was composed of a lower shallow marine sand, silt and clay, and an upper fluvial sand and gravel. Deformation at this site led to the formation of large anticlines in the silts and clays, with disharmonic smaller folds and thrusts in the upper gravels, above a detachment surface between the fine-grained and overlying coarse-grained lithologies. This resulted in a longitudinally extensive push moraine, with a relatively low-amplitude (in the upper gravels) folded and thrust surface. This style of push moraine is very common, and is very similar in size, deformation style and longitudinal strain to a number of others described in the literature, e.g. Holmströmbreen (Gripp, 1929; Boulton *et al.*, 1989), Maktak glacier, Baffin Island (Boulton, 1986), Thompson glacier, Axel Heiberg (Kälin, 1971; Lehmann, 1992) and Eyjabakkajökull, Iceland (Croot, 1988c).

In contrast, the push moraine at Finsterwalderbreen was more unusual in style. This was formed by a series of advances and was formed from the proglacial deformation of a previous outwash plain. This moraine was much shorter in longitudinal extent, although of similar height to the Penckbreen moraine. We suggest that the moraine was less longitudinally extensive at Finsterwalderbreen because it was composed of a more competent material than Penckbreen (i.e. a more gravel-rich lithology and without an obvious fine-grained décollement surface), and the presence of previously formed push moraines. Although gravel-rich moraines have been recorded in the past (e.g. Turtmann glacier, Switzerland (Eybergen, 1987)), push moraines composed of different aged elements have received little attention (with the exception of Usherbreen). At Finsterwalderbreen, it was shown that the surge events all reached a similar limit and occurred at regular intervals.

This study has highlighted the importance of sediment competence and glacial history in the formation of push moraines, and has shown how adjacent glaciers can produce different styles of moraine.

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